Frascati Physics Series Vol. nnn (2001), pp. 000-000
Title Conference - Conference Town, Date dd mm, 2001

HIGH PRECISION COSMOLOGY

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ABSTRACT

I review the current status of cosmology as emerging from recent observations of cosmic microwave background anisotropies as well as from other sources of cosmological information.

1 Introduction

The widely accepted paradigm for cosmology is the hot Big Bang model. In this framework, the geometry and evolution of the Universe is defined by its matter and energy content through general relativity theory. The Universe is expanding, so that it was hotter and denser at earlier times. The rate of expansion is quantified by the Hubble parameter H, whose present value H_0 is parameterized by the quantity h as $H_0 = 100\ h$ km s^{-1} Mpc^{-1}. The amount of matter and energy in the Universe from different components (baryons, dark matter, radiation, vacuum energy, etc.) is parameterized by the quantities $\Omega_{(i)} \equiv \rho_{(i)}/\rho_c$. The critical density, $\rho_c = 1.88 \times 10^{-29}\ h^2$ g cm^{-3}, is defined in such a way that $\Omega \equiv \sum_i \Omega_{(i)} = 1$ for a Universe with flat geometry (while $\Omega < 1$ and $\Omega > 1$ for open and closed geometry respectively).

An additional ingredient of the standard cosmological model is *inflation* [1], a phase of early superluminal expansion of the Universe required to solve some problems of the Big Bang model. Inflation makes some well-defined predictions. First of all, the geometry of the Universe has to be very close to flat. Second, the structure we observe today in the Universe was produced by gravitational amplification of primordial density perturbations generated during inflation, characterized by having a nearly scale-invariant spectrum and by being Gaussian distributed.

While until recent times the knowledge of the parameters of the cosmological model was plagued by large uncertainties, the situation has now dramatically changed. Cosmology is not a data-starved science anymore. In the past few years, high-quality observations have fueled an impressive progress in our understanding of the Universe. We have entered the epoch of high precision cosmology.

Recent results from observation of the CMB temperature anisotropy have allowed us to constrain most cosmological parameters to unprecedented accuracy, giving for the first time a robust determination of the total energy density (and in turn of the geometry) of the Universe. In addition, a whole set of new observations of the large-scale structure properties of the Universe have put the determination of the mean matter density in the Universe on a firm ground. Finally, measurements of distant Type Ia Supernovae have recently provided evidence that the Universe has just entered a phase of accelerated expansion. In the following I will review the emerging scenario, giving particular emphasis to CMB as a cosmological probe.

2 Cosmology with the Cosmic Microwave Background

The Cosmic Microwave Background (CMB) is a snapshot of the infant Universe, when it was just about 300 000 years old. According to the standard Big Bang model, before that epoch the temperature in the Universe was so high that no neutral atom could stably exist. The Universe was basically a plasma of mainly free electrons and protons, kept in equilibrium with photons by frequent Thomson scattering. Later, the Universe cooled down as a result of the expansion, and neutral atoms began to form. The photons could then decouple from the matter and travel freely, being finally observed today as an almost uniform background. The fact that the CMB was indeed found to have a black-body spectrum (a clear signature of the early period of matter-radiation equilibrium) with an astonishing precision [2] is one of the big successes of the Big Bang model.

Since the distribution of the CMB photons reflects that of matter at the time of decoupling, any inhomogeneities in the matter density (needed to seed structure formation by gravitational instability) must leave an imprint as fluctuations of the CMB temperature. The presence of these *CMB temperature anisotropies* was first detected by NASA's COBE satellite in the early 90's [3]. The fact that the level of anisotropy is very small (about a part in one thousand, corresponding to temperature fluctuations of some tens of μK) simplifies the task of making theoretical prediction of the anisotropy pattern, since linear perturbation theory can be applied.

The bulk of the cosmological information encoded in the anisotropy pattern is concentrated at angular scales smaller than about 1 degree on the sky, corresponding to perturbations that were inside the horizon (i.e. in causal contact) before decoupling. On these scales, physical processes in the early Universe were able to leave their imprint on the CMB. For this reason, over the last decade a large number of ground-based and balloon-borne experiments performed observations of the fine-structure pattern of the anisotropy.

The observed temperature fluctuation in a given direction of the sky can be expanded in spherical harmonics:

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi). \tag{1}$$

The coefficients $C_l \equiv \langle |a_{lm}|^2 \rangle$ define the *angular power spectrum* of the CMB anisotropy[1]. Because the Universe is isotropic on average, the C_l's do not depend on the azimuthal index m. If the primordial density fluctuations are

[1] The symbol $\langle \cdot \rangle$ represents an average over the statistical ensemble. Since we can only observe one realization of the ensemble — our own sky — we can at best build an un-biased estimate of C_l from the observations. This is: $C_l \equiv \frac{1}{(2l+1)} \sum_{m=-l}^{l} |a_{lm}|^2$.

Gaussian distributed, the angular power spectrum C_l fully characterizes the statistics of the temperature anisotropy pattern. The power spectrum is then the main CMB observable. Since each l is related to an angular scale θ on the sky given approximately by $l \sim \pi/\theta$, the power spectrum at high l's probes sub-horizon angular scales at the time of decoupling and carries the imprint of physical processes which occurred in the early Universe. Conversely, low l's probe the primordial shape of the power spectrum[2].

The way the shape of the CMB angular power spectrum depends on cosmology can be understood by simple physical considerations. Let us consider a density fluctuation of given physical scale in the baryon-photon fluid. Let us suppose that the physical scale of the fluctuation is smaller than the horizon size at decoupling, so that the inner region of the fluctuation is in causal contact. The amplitude of perturbation in the baryon component tends to be amplified by gravitational collapse. However, the radiation pressure provided by the photons prevents the collapse from happening. These competing mechanisms sets up harmonic oscillations in the amplitude of the perturbation. Since the amount of resistance to compression is quantified by the sound velocity in the fluid, this oscillations are called *acoustic*. When the photons decouple from matter, perturbations having different physical scale are caught in a different stage of oscillation and then have a different amplitude. The CMB photons we receive today carry this phase information as fluctuations in their temperature at different angular scales. This reflects in a series of harmonic acoustic peaks in the CMB angular power spectrum.

For a given initial distribution of density perturbations in the early Universe, the height of the acoustic peaks is mostly affected by the amount of matter in the Universe. If we enhance the baryon content of the Universe, keeping fixed all the other components, the compression stage of the fluid is more effective, increasing the amplitude of fluctuations at decoupling. Then, the relative height of the peaks in the CMB power spectrum represents a good indicator of the density of baryonic matter in the Universe. On the other hand, the position of the peaks depends on the way a certain physical scale at decoupling is mapped into an angular dimension on the sky. This is quantified, in a given cosmological model, by the so called *angular diameter distance relation*.

[2] Of course, neglecting secondary processes which may alter the CMB photon distribution after decoupling.

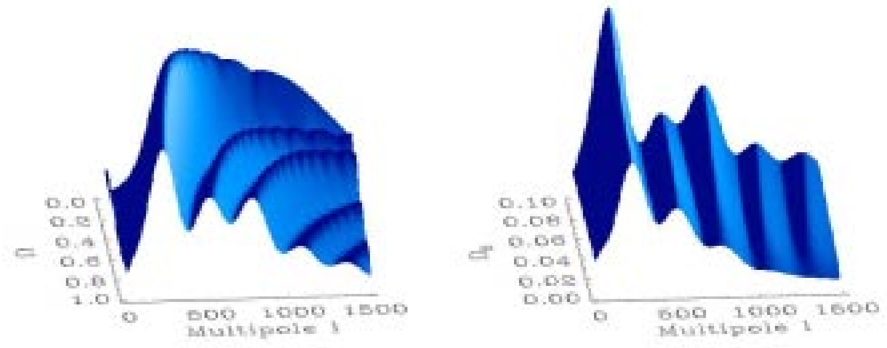

Figure 1: *The effect of cosmological parameters on the peak structure of the CMB angular power spectrum. On the left, the effect of varying the total energy density while keeping all the other parameters fixed. On the right, the effect of varying the baryon density.*

This relation mainly depends on the geometry of the Universe: in an open Universe, a certain physical scale at decoupling is seen today under a smaller angle than in a flat Universe. So, the position of the peaks in the CMB angular power spectrum is a good indicator of the geometrical properties of the Universe. The dependence of the CMB angular power spectrum on the geometry of the Universe and on the baryon density is shown in Figure 1.

3 Constraints on Cosmological Parameters from the CMB

The quality of CMB observations has considerably improved in recent times. The balloon-borne observations carried on by the BOOMERanG [4)] and MAXIMA [5)] teams (from Antarctica and from Texas, respectively) have produced the first images of the fine-scale pattern of CMB temperature anisotropy. The CMB map from BOOMERanG covers a 1800 square degrees patch of the southern sky. MAXIMA mapped a 124 square degrees patch of the northern sky. More recently, the DASI [6)] team released new maps over 32 sky fields of 3.4 degrees in diameter, obtained using ground-based interferometry from Antarctica. The kind of spatial features observed by these three independent experiments in different sky regions looks quite similar (see Figure 2).

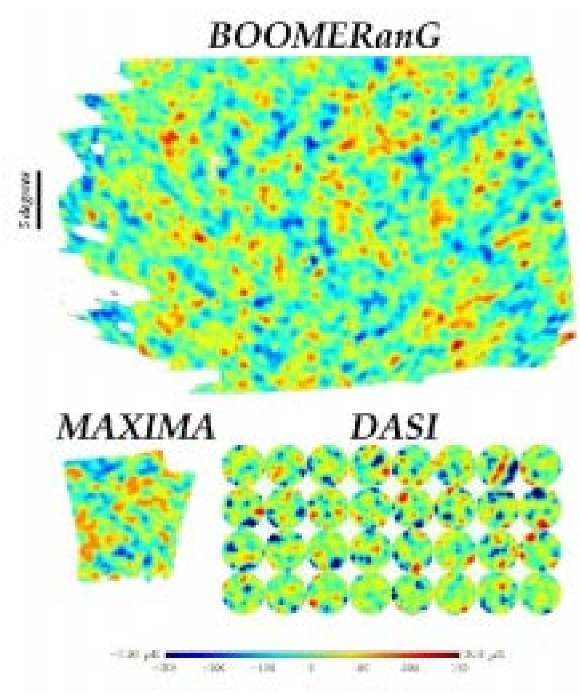

Figure 2: *Maps of the CMB temperature anisotropy produced by the BOOMERanG, MAXIMA and DASI experiments.*

From these observations, estimates of the CMB angular power spectrum have been obtained over a large range of multipoles ($20 \leq l \leq 1200$; see Figure 3). The power spectra measured by BOOMERanG, MAXIMA and DASI are in remarkable agreement and show unambiguously the presence of a sharp peak in the region $180 \leq l \leq 220$, as well as evidence of excess power at higher l's, consistent with the presence of a second and third peak.

Likelihood analyses of these power spectrum measurements have been performed by each team to set constraints on the value of cosmological parameters. They agree about the fact that the CMB data strongly favor a Universe with flat geometry, and with scale-invariant primordial density fluctuations: the inflationary scenario brilliantly passed two important tests. Furthermore, the baryon density derived from the CMB is in striking agreement with the value resulting from comparing the measured primordial light elements abundances

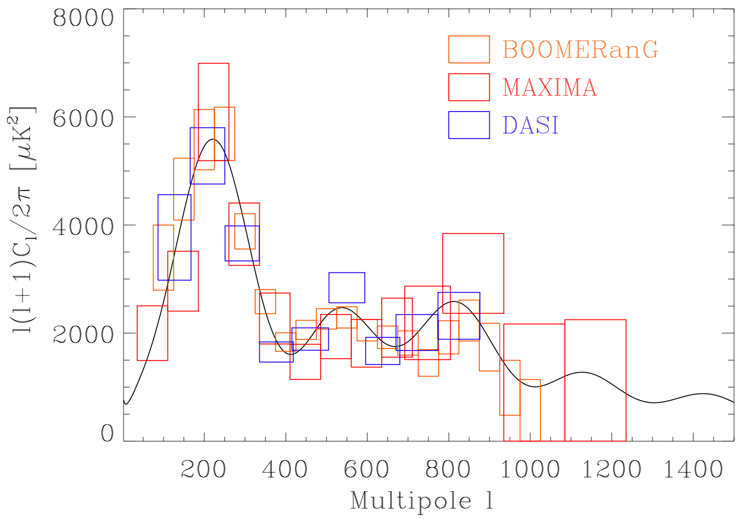

Figure 3: *Measurements of the CMB angular power spectrum from BOOMERanG, MAXIMA and DASI. The continuous line a reference theoretical model for a flat cosmology.*

with the big bang nucleosynthesis (BBN) predictions: $\Omega_b h^2 = 0.020 \pm 0.002$ [7]. This is an important indication of the self-consistency of our cosmological model, since the CMB and BBN values for the baryon density are obtained using entirely different methodology and observations.

4 The Concordance Model

The success of the CMB in giving us a reliable estimate of the total energy density of the Universe leaves us with the problem of finding out which is the contribution from different components to the critical density. Measuring the mean mass density of the Universe with traditional cosmological observations has always been a difficult task. Large enough samples have to be observed in order to be representative of the whole Universe. Furthermore, the distribution of matter cannot be directly deduced from that of light. However, the matter density is currently constrained by a number of independent and consistent observations (baryon-to-total mass ratio in clusters of galaxies, peculiar velocities and bulk flows, redshift surveys) to be roughly 1/3 of the total energy density ($\Omega_M = 0.33 \pm 0.04$ [8]). Where does the rest of critical density comes from?

Observations of distant type Ia supernovae [9] recently allowed to probe the classic Hubble diagram up to very high redshifts. The surprising result was that, contrarily to expectations, the Universe is speeding up rather than slowing down. The fact that we are now entering a phase of cosmic acceleration has been explained with the presence of a smooth, negative-pressure component, which has been named *dark energy*. The best candidate for dark energy is a cosmological constant, or vacuum energy, i.e. the vacuum expectation value of some fundamental scalar field.

Cosmological models with flat geometry but different amount of vacuum energy have almost the same angular diameter distance relation. This makes the CMB angular power spectrum basically unable to distinguish which fraction of the critical density is provided by matter and which by the vacuum energy. However, when we look at the constraints in the Ω_M—Ω_Λ plane coming from the CMB, the observation of large-scale structure (LSS) and type Ia supernovae (SN Ia) an interesting picture emerges (see Figure 4). The CMB and the LSS suggest that 2/3 of the critical density must be provided by vacuum energy. The CMB and the SN Ia get to the same conclusion. The three constraints taken together identify a *concordance* region in the parameter space where $\Omega_M \sim 1/3$, $\Omega_\Lambda \sim 2/3$, and $\Omega = \Omega_M + \Omega_\Lambda \sim 1$. The fact that three independent and different kinds of observation, each probing a different epoch of the cosmic evolution and different physical processes, have converged to give a coherent picture is a big success of cosmology.

5 Future Prospects

While a consistent and reliable picture of the Universe is emerging, there are still open questions. One of the most puzzling aspects is the nature of the dark energy which seems to be the main contribution to the density of the Universe. The vacuum energy estimated from quantum field theory (as vacuum expectation value of some fundamental quantum field) is 10^{122} to 10^{55} times larger than the observed one, which leads to an extreme *fine-tuning* problem. Furthermore, vacuum energy is dominating the cosmic expansion right now, which seems to make the present epoch a very special one in the evolution of the

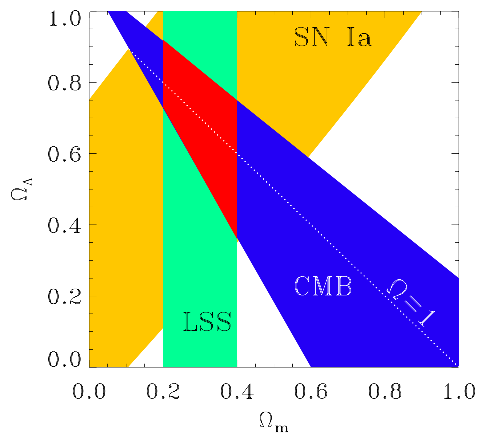

Figure 4: *Likelihood contours (95% confidence level) from CMB, supernovae and large-scale structure observations.*

Universe (*coincidence* problem). This problems are mitigated in the so-called *quintessence* models, where the scalar field responsible for the vacuum energy contribution is evolving through an equation that admits *tracking solutions*: large set of initial conditions result in the same vacuum energy at present. Attempts to use current CMB data to investigate the nature of dark energy have recently been made [10)].

Future CMB missions from space will shed more light on this and other open problems. The NASA's MAP mission[3] is currently operating and will soon produce full sky maps of the CMB sky at high angular resolution. In 2007 the ESA's Planck satellite[4] will measure CMB temperature and polarization over the full sky with unprecedented angular resolution and instrumental sensitivity, reaching the theoretical limit in the power spectrum measurement over a large range of multipoles ($2 \leq l \leq 3000$). This observations, together with other sources of information (most notably further supernovae measurements from space such as those expected from the SNAP satellite[5] and redshift surveys

[3]http://map.gsfc.nasa.gov/
[4]http://astro.estec.esa.nl/Planck
[5]http://snap.lbl.gov

such as SDSS[6]) will further strengthen our understanding of the Universe.

6 Acknowledgements

It is a pleasure to thank the organizers for the invitation and for the enjoyable and stimulating environment.

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[6] http://www.sdss.org